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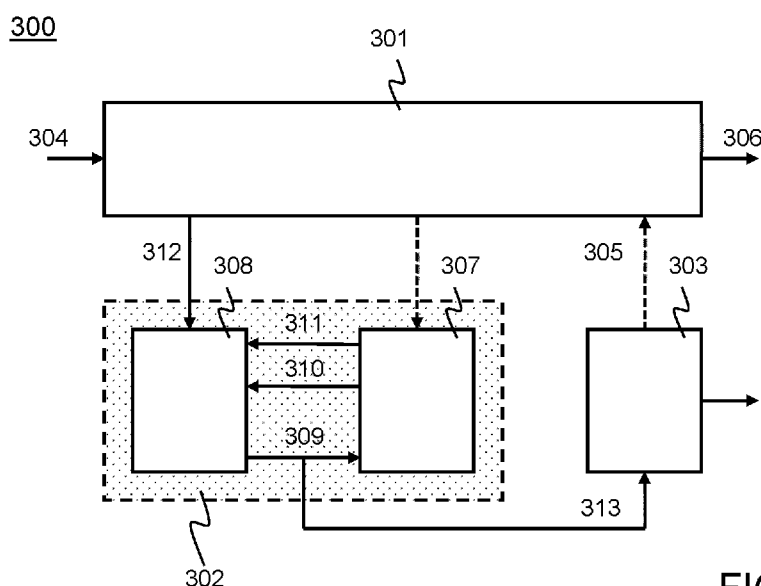


FIG. 3

(57) Abstract: A wake produced by a leader aircraft and experienced by a follower aircraft is sensed by repetitively carrying out the following two operations in an iterative manner. Measurements carried out by the follower aircraft are estimated (311) based on a simulated response of the follower aircraft to an estimated aerodynamic context (309). The estimated aerodynamic context (309) includes, on the one hand, a model of the wake and an estimated position of the follower aircraft with respect to the model of the wake and, on the other hand, data indicating aerodynamic effects experienced by the follower aircraft due to its own motion. The estimated aerodynamic context (309) is adjusted (308) based on a comparison between the measurements that have been estimated (311) and actual measurements (312) carried out by the follower aircraft, aiming to reduce a deviation between the measurements that have been estimated and the actual measurements. Information (313) on the wake is extracted from the estimated aerodynamic context (309).

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Aircraft wake sensing.

FIELD OF THE INVENTION

An aspect of the invention relates to a method of sensing a wake produced by a leader aircraft and experienced by a follower aircraft. The method may be used, for example, when aircraft fly in formation, whereby these aircraft may be civil aircraft. The method may be carried out, for example, by a flight computer in a follower aircraft. Further aspects of the invention relate to a flight control method, a computer program, and a flight computer.

BACKGROUND ART

Aircraft may fly in formation whereby a follower aircraft flies behind a leader aircraft. The follower aircraft may experience a wake generated by the leader aircraft. This may have a beneficial effect or an adverse effect depending on the wake and on the position of the follower aircraft in the wake. For example, an appropriate position may provide drag reduction for the follower aircraft, which may result in fuel savings.

The follower aircraft may comprise a so-called peak seeking system that finds and maintains a desired position in the wake. In order to do so, the peak seeking system needs to obtain information on the wake and on the present position of the follower aircraft in the wake. This information may be obtained, at least partially, through a communication link between the leader aircraft and the follower aircraft. Information on the wake may also, or additionally, be provided by specific measurement equipment, such as, for example, light ranging and detection (LIDAR) equipment or dedicated pressure probes, or a combination of these.

Patent publication US2014214243A1 describes an apparatus for controlling a formation flight of a trailing aircraft relative to a vortex generated by a leading aircraft. In the apparatus, a position module determines a position of the vortex relative to the trailing aircraft. A peak-seeking module determines a desired position of the trailing aircraft for providing desired vortex-induced aerodynamic benefits based on the position of the vortex relative to the trailing aircraft and a mapping function of an individual performance metric. A limiter module modifies the desired position of the trailing aircraft to avoid unintended crossings of the trailing aircraft into the vortex. A control module controls flight of the

trailing aircraft based the desired position of the trailing aircraft or the modified desired position of the trailing aircraft.

SUMMARY OF THE INVENTION

5 There is a need for an improved solution that allows a follower aircraft to obtain information on a wake produced by a leader aircraft, whereby an improvement resides in at least one of the following aspects: ease of implementation and cost.

 In accordance with an aspect of the invention as defined in claim 1, there is provided a method of sensing a wake produced by a leader aircraft and experienced by a
10 follower aircraft, the method comprising repetitively carrying out the following two operations in an iterative manner:

- estimating measurements carried out by the follower aircraft based on a simulated response of the follower aircraft to an estimated aerodynamic context that includes, on the one hand, a model of the wake and an estimated position of the follower
15 aircraft with respect to the model of the wake and, on the other hand, data indicating aerodynamic effects experienced by the follower aircraft due to its own motion; and
 - adjusting the estimated aerodynamic context based on a comparison between the measurements that have been estimated and actual measurements carried out by the follower aircraft, aiming to reduce a deviation between the measurements that have
20 been estimated and the actual measurements;
- the method further comprising:
- extracting information on the wake from the estimated aerodynamic context.

 The method exploits the fact that a part of an estimated aerodynamic context
25 concerns the follower aircraft itself. This part can be estimated relatively accurately through modeling and measurements. In fact, in the absence of a wake, the actual measurements will match measurements estimated on the basis of aircraft modeling quite well. The wake is a disturbance, which creates a deviation between estimated measurement and actual measurements. This deviation is exploited to learn more about the wake based
30 on general a priori knowledge of the wake expressed by the model of the wake. Iterations based on adjusting the estimated aerodynamic context, which comprises a relatively well-known part concerning the follower aircraft itself and a part to know better, the wake, reduces the deviation and thus provide information about the wake.

The method allows the follower aircraft to obtain information on the wake, and an indication of its position therein, using measurement equipment and control software that is typically already present in aircraft, in particular in commercial aircraft. The follower aircraft need not comprise specific, additional measurement equipment for wake sensing. Sufficiently accurate and precise wake sensing may easily and cost-effectively be achieved by adding software to a flight computer, which enables a processor in the flight computer to carry out the method defined hereinbefore. What is more, the wake sensing method can be carried out without communication between the leader aircraft and the follower aircraft.

In accordance with a further aspect of the invention as defined in claim 12, there is provided a method of controlling a flight of a follower aircraft that flies behind a leader aircraft. In accordance with yet further aspects of the invention, there is provided a computer program and a flight computer as defined in claims 14 and 15, respectively.

For the purpose of illustration, some embodiments of the invention are described in detail with reference to accompanying drawings. In this description, additional features will be presented, some of which are defined in the dependent claims, and advantages will be apparent.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a pictorial diagram of a flight situation with a leader aircraft and a follower aircraft.

FIG. 2 is a conceptual diagram of an aerodynamic context experienced by the follower aircraft.

FIG. 3 is a block diagram of a flight computer in the follower aircraft, which comprises a wake estimator.

FIG. 4 is a functional diagram of an embodiment of the wake estimator.

DESCRIPTION OF SOME EMBODIMENTS

FIG. 1 schematically illustrates a flight situation with a leader aircraft 101 and a follower aircraft 102. FIG. 1 provides a pictorial diagram of this flight situation. The leader aircraft 101 has a standard structure comprising a main wing 103, a vertical tail

plane 104, and a horizontal tail plane 105. The same applies to the follower aircraft 102, which also has a main wing 106, a vertical tail plane 107, and a horizontal tail plane 108.

The leader aircraft 101 generates a wake 109. The wake 109 may comprise two vortices 110, 111. One wake vortex 110 emanates from a tip of the main wing, another
5 wake vortex 111 emanates from the other tip of the main wing. In general, generation of lift leads to a flow below a wing, around a tip of the wing into a region above the wing where pressure is lower. This generally generates a vortex at the tip of the wing.

The follower aircraft 102 may experience the wake 109 generated by the leader aircraft 101. That is, the follower aircraft 102 experiences an aerodynamic context
10 that may include this wake 109. The two wake vortices 110, 111 generate vertical wind patterns, which may positively or negatively affect flight conditions for the follower aircraft 102. This depends on a position of the follower aircraft 102 in the wake 109, in particular the position with respect to the two wake vortices 110, 111. In case the follower aircraft 102 is appropriately positioned in the wake 109, the follower aircraft 102 may
15 experience drag reduction, which allows fuel savings.

The aforementioned may also apply when the follower aircraft 102 is flying at a relatively large distance behind the leader aircraft 101. This is typically the case in civil aviation where a minimum distance between aircraft should be respected for safety reasons. For example, the follower aircraft 102 may be flying at several tens of wingspans
20 downstream of the leader aircraft 101. Nonetheless, even at such distances, the follower aircraft 102 may still benefit from a positive interaction with the wake vortices 110, 111. This is because these are generally long-lasting and thus extend over relatively large distances with sufficient intensity.

However, drag reduction is very sensitive to a positioning of the follower
25 with respect to the wake vortices 110, 111. What is more, the wake vortices 110, 111 may vary in location due to instabilities, such as, for example, wake meandering, and due to external factors, such as, for example, a meteorological phenomenon. It is therefore desired that the follower aircraft be able to continuously locate and track the wake vortices at a sufficiently high accuracy. This allows the follower aircraft 102 to maintain an
30 advantageous position in the wake 109, in terms of, for example, fuel saving, flight safety, or flight comfort, or a combination thereof.

FIG. 2 schematically illustrates an aerodynamic context 200 experienced by the follower aircraft 102. FIG. 2 provides conceptual diagram of the aerodynamic context 200. The follower aircraft 102 is located at an inertial position 201 designated in FIG. 2.

The wake 109 of the leader aircraft 101 is modeled as two counter-rotating vortex tubes 202, 203 of circulation jointly designated by the symbol Γ . In this wake model 204 there is a spacing 205 between these vortex tubes 202, 203 and a center line 206 along which the vortex tubes 202, 203 are aligned. The vortex tubes 202, 203 are further aligned
 5 along an inertial axis x_i of a Cartesian coordinate system x_i, y_i, z_i indicated in FIG. 2.

The follower aircraft 102 has a position 207 with respect to the wake model 204 that is defined as relative to the center line 206. More specifically, this relative position 207 is expressed as an offset $\Delta y(t)$ along an y axis of the aforementioned coordinate system, and an offset $\Delta z(t)$ along a z axis. These offsets $\Delta y(t)$, $\Delta z(t)$ can be
 10 regarded as a side distance and a height distance, respectively. In addition, the follower aircraft 102 has an angular position with respect to the wake model 204.

The follower aircraft 102 is modelled by means of a main wing 208 characterized by a center and a span, a horizontal tail plane 209 having a span, and a vertical tail plane 210 having a span. The aforementioned tail planes 209, 210 are located
 15 at a distance from the center of the main wing 208. In this embodiment, a wake of the follower aircraft 102 is modeled as a flat vortex sheet 211 extending backwards from the main wing 208, and two perpendicular vortex sheets produced by the vertical tail plane and the horizontal. All those vortex sheets are assumed to go straight to infinity. The flat vortex sheet 211 from the main wing 208 induces a downwash on the tail of the follower aircraft
 20 102. This downwash may be modeled as a horseshoe vortex. Accordingly, loads on the tail, which affect a longitudinal and a lateral behavior of the follower aircraft 102 may be taken into account.

The wake of the leader aircraft represented by the model 204 induces flow velocities on the main wing 208, the horizontal tail plane 209, and the vertical tail plane
 25 210. These wake-induced flow velocities depend on the relative position 207 of the follower aircraft 102 as well as its angular position with respect to the wake model 204, in addition to the translational and angular speeds of the follower aircraft 102. The wake-induced flow velocities may be combined with a modeled dynamic behavior of the follower aircraft 102 to determine a relative flow velocity vector. Aerodynamic angles,
 30 such as, for example, angle of attack α and angle of slip β may be computed from the relative flow velocity vector being perceived at a center of mass of the follower aircraft 102.

Lift and drag forces and moments experienced by the follower aircraft 102 may be estimated on the basis of a lifting line theory, such as, for example, the Prandtl

lifting line theory. Given a set of lifting lines, a circulation distribution may be calculated along each lifting line by solving an integro-differential equation that relates circulation with relative flow velocity. The relative flow velocity is a combination of various flow velocities, which are induced by movement of the follower aircraft 102, by the wake 109 of the leader aircraft 101, and by the lifting lines themselves. The lift and drag forces and the moments can be deduced from circulation distributions that have been calculated in this manner.

A model simulating dynamic behavior of the follower aircraft 102 may take into account the lift and drag forces and moments experienced by the follower aircraft 102.

This model, which will be referred to hereinafter as aircraft simulator, operates on variables representing six degrees of freedom: position on a longitudinal axis, position on a transverse axis, position on a height axis, angle of roll, angle of pitch, and angle of yaw. The aircraft simulator may further operate on the time derivatives of these six degrees of freedom, which are speed along the longitudinal axis, speed along the transverse axis, speed along the height axis, roll rate, pitch rate, and yaw rate.

The aircraft simulator may predict position and velocity of the follower aircraft 102. The aircraft simulator may thus predict a change in the aerodynamic context 200 illustrated in FIG. 2. A translation or a rotation, or both, of the follower aircraft 102, as well as a translation or a rotation, or both, of the wake model 204, may change air velocities along the lifting lines mentioned hereinbefore. This, in turn, may affect the lift and drag forces and moments experienced by the follower aircraft 102, which may change the aforementioned aerodynamic angles as well as other measurable aerodynamic parameters. Since the aircraft simulator takes into account the lift and drag forces and moments, there is thus a strong coupling between the aerodynamic context 200 illustrated in FIG. 2 and the aircraft simulator.

FIG. 3 schematically illustrates a flight computer 300 in the follower aircraft 102. FIG. 3 provides a block diagram of the flight computer 300. The flight computer 300 comprises various functional entities, which are schematically represented as blocks: a flight controller 301, a wake estimator 302, and a wake analyzer 303. Any of these functional entities may be implemented, at least partially, by means of a computer program that enables a processor in the flight computer 300 to carry out various operations. These operations will be described hereinafter in relation with the functional entity concerned. The operations that the flight controller 301, the wake estimator 302, and the wake

analyzer 303 carry out constitute a flight control method, a wake sensing method, and a wake analysis method, respectively.

The flight computer 300 basically operates as follows. The flight controller 301 receives data 304 of various measurements that the follower aircraft 102 carries out.

5 These measurements may comprise measurements typically carried out by commercial aircraft. The latter measurements may include at least one of the following: angle of incidence, angle of slip, inertial position, velocity, attitude, angular velocity, as well as translational and angular accelerations.

The flight controller 301 further receives a target trajectory 305. The target
10 trajectory 305 may at least partially be defined by output data from the wake analyzer 303. For example, the output data from the wake analyzer 303 may indicate positions in the wake 109 of the leader aircraft 101 where the follower aircraft 102 may benefit from drag reduction. The output data of the wake analyzer 303 may further provide indications of drag reduction benefits associated with these positions. This will be described in greater
15 detail hereinafter.

The flight controller 301 provides control outputs 306 on the basis of measurement data and the target trajectory 305 to be followed. The flight controller 301 may include a so-called autopilot that implements a control strategy on which the control outputs 306 are based.

20 The wake estimator 302 basically comprises two functional entities: a dynamic response simulator 307 and an estimation adjuster 308. The dynamic response simulator 307 receives an estimated aerodynamic context 309. The estimated aerodynamic context 309 includes a model of the wake and an estimated position of the follower aircraft 102 with respect to the model of the wake. This has been illustrated in FIG. 2. The model
25 of the wake may thus correspond to the wake model 204 illustrated in FIG. 2 described hereinbefore. The estimated aerodynamic context 309 may include further data indicating flow velocities experienced by the follower aircraft 102 due to, for example, its own motion, as well its operational state. For example, this further data of the aerodynamics may comprise the aforementioned six degrees of freedom of the follower aircraft 102 and
30 the time derivatives of these. The data indicating the operational state of the follower aircraft may pertain to flight control surfaces and thrust. The data may comprise control inputs for these.

The dynamic response simulator 307 provides a simulated response 310 of the follower aircraft 102 to an estimated aerodynamic context 309. The simulated response

310 may be based on the aircraft simulator mentioned hereinbefore. In fact, the dynamic response simulator 307 may be regarded as a flight simulator in the sense that the dynamic response simulator 307 should provide a sufficiently accurate representation of an actual dynamic response of the follower aircraft 102. Since, in flight, the follower aircraft 102
5 will generally have a relatively strong non-linear dynamic behavior, the dynamic response simulator 307 will typically provide the simulated response 310 on the basis of non-linear functions.

The simulated response 310 of the follower aircraft 102 provides an estimate 311 for at least some of the measurements that the follower aircraft 102 carries
10 out. These estimated measurements 311 based on the simulated response 310 may include measurements that depend on an actual aerodynamic context perceived by the follower aircraft 102. Examples of such measurements include angle of incidence and angle of slip, mentioned hereinbefore in relation with the aerodynamic context 200 illustrated in FIG. 2, as well as other aerodynamic parameters, such as, for example, position, speed, and
15 acceleration.

The estimation adjuster 308 compares the estimated measurements 311 based on the simulated response of the follower aircraft 102 with corresponding actual measurements 312 that the follower aircraft 102 carries out. The estimation adjuster 308 then adjusts the estimated aerodynamic context 309 on the basis of this comparison. A
20 degree of adjustment may depend on indications of uncertainty, that is, possible errors, in the estimated measurements 311 and in the actual measurements 312. For example, in case the estimated measurements 311 are relatively uncertain whereas the actual measurements 312 are relatively precise, that is, reliable, the degree of adjustment will be relatively high. Conversely, in case confidence in the estimated measurements 311 is relatively large
25 compared with possible errors in the actual measurements 312, the degree of adjustment will be relatively low.

Accordingly, the dynamic response simulator 307 will receive a new estimated aerodynamic context 309, which is an adjustment of the estimated aerodynamic context 309 that the dynamic response simulator 307 has previously received. The dynamic
30 response simulator 307 may then provide a new simulated response 310 of the follower aircraft 102 to the new estimated aerodynamic context 309. New estimated measurements 311 may then be provided and compared with the actual measurements 312, which may have evolved in the meantime.

This process, which has been described hereinbefore, may iteratively continue and provide a relatively accurate estimation of the aerodynamic context. Since this context includes a model of the wake, information 313 on the wake 109 may be extracted from this estimation. Moreover, a relatively precise indication of the position of the follower aircraft 102 in the wake 109 may be obtained.

A remarkable feature is that the information 313 on the wake 109 and the indication of the position therein may be obtained using measurement equipment and control software that is typically already present in aircraft, in particular in commercial aircraft. The follower aircraft 102 need not comprise specific, additional measurement equipment for wake sensing. Sufficiently accurate and precise wake sensing may be achieved by adding software to the flight computer 300, which functionally provides the wake estimator 302 described hereinbefore. What is more, the wake sensing can be carried out without communication between the leader aircraft 101 and the follower aircraft 102.

Nonetheless, although not essential, the wake estimator 302 may benefit from information on the leader aircraft 101, for example, in order to improve efficiency or accuracy, or both. The information of the leader aircraft 101 may concern, for example, aircraft type, aircraft mass, or aircraft position, or any combination of these. The follower aircraft 102 may obtain this information through a communication link with the leader aircraft 101. The communication link may use, for example, an ADS-B protocol.

In this embodiment, the wake analyzer 303 processes the information 313 on the wake 109 that is extracted from the estimated aerodynamic context 309. The wake analyzer 303 may filter this information 313, which may have a noisy nature. This filtering may comprise, for example, techniques such as Gaussian filtering. The wake analyzer 303 can then detect generic patterns of the wake 109 based on the information 313 that has been filtered. The wake analyzer 303 may also detect a turbulence characteristic in the wake 109. The generic patterns of the wake 109 that have been detected may be used to predict behavior of the wake 109. The wake estimator 302 may use these wake predictions to increase accuracy or to achieve a desired level of accuracy faster, with fewer iterations. The wake analyzer 303 may provide the target trajectory 305 to the flight controller 301, as mentioned hereinbefore, in order to maintain a position allowing drag reduction, or otherwise enhance flight performance, safety, and passenger comfort.

FIG. 4 schematically illustrates an embodiment 400 of the wake estimator 302. FIG. 4 provides a functional diagram of this embodiment 400, which will be referred to as the wake estimator 400 for the sake of convenience. The wake estimator 400

illustrated in FIG. 4 is based on an ensemble Kalman filter architecture, which is one of various possible architectures as will be indicated hereinafter. In this embodiment, the wake estimator 400 comprises an aircraft state propagator 401, a measurement estimator 402, a comparator 403, an analyzer 404, and a covariance inflator 405.

5 In the wake estimator 400, an estimated aerodynamic context 406 is represented by a set of state vectors 407-411. In FIG. 4, five state vectors are represented for the sake of simplicity and convenience. In practice, the set of state vectors 407-411 may be larger. A state vector comprises a set of variables defining a possible aerodynamic context. In FIG. 4, variables are schematically represented by means of pictorial symbols.

10 A group of variables 412 in the state vector relate to a wake model that is used, such as, for example, the wake model 204 illustrated in FIG. 2. Another group of variables may relate to the six degrees of freedom of the follower aircraft 102 and their derivatives mentioned hereinbefore. The state vector may comprise further variables that relate to measurement biases that can be taken into account.

15 The set of state vectors 407-411 thus represent various possible aerodynamic contexts. A mean vector can be calculated from the set of state vectors 407-411. The mean vector represents the estimated aerodynamic context 406. The set of state vectors 407-411 has a degree of heterogeneity that expresses a degree of uncertainty about the estimated aerodynamic context 406. In case the state vectors 407-411 in the set differ

20 from each other to a relatively great extent, the degree of uncertainty is relatively high. Conversely, in case the state vectors 407-411 are relatively similar, the degree of uncertainty is relatively low. In that case, there is confidence the estimated aerodynamic context 406, which is expressed by the mean vector of the set.

The aircraft state propagator 401 generates a model-based new set of state

25 vectors on the basis of a present set of state vectors 407-411. The model-based new set of state vectors represent a new estimated aerodynamic context 413 that is expected on the basis of a model of the follower aircraft 102 given the estimated aerodynamic context 406 that is presented as an input to the model. For a state vector of the set presented as an input, the aircraft state propagator 401 may calculate a new state vector by applying a complex

30 non-linear matrix function that models the dynamic behavior of the follower aircraft 102. That is, the aircraft state propagator 401 may functionally be regarded as the aircraft simulator mentioned hereinbefore.

The measurement estimator 402 provides estimated measurements 414 on the basis of the model-based new set of state vectors. The estimated measurements 414 are

also expressed by means of a set of measurement vectors, similar to the estimated aerodynamic context 406 being expressed by the set of state vectors 407-411. The measurement estimator 402 may calculate a measurement vector from a new state vector by applying a matrix function to the new state vector. The matrix function models
5 measurements that are carried out by the follower aircraft 102.

The comparator 403 compares the estimated measurements 414 with actual measurements 415 carried out by the follower aircraft 102. The actual measurements 415 may also be expressed by means of a set of measurement vectors. Random differences may be enforced between measurement vectors in the set. This may be achieved by adding a
10 random vector to a vector that comprises the actual measurements. This addition of randomness to the actual measurements may prevent spurious correlation in a measurement comparison result 416 that the comparator 403 provides. The measurement comparison result 416 is also expressed by means of a set of comparison vectors. A comparison vector is obtained by subtracting two corresponding measurement vectors from
15 each other, one vector from the set representing actual measurements 415, the other vector from the set representing estimated measurements 414.

The analyzer 404 generates an aerodynamic context adjustment on the basis of the measurement comparison result 416. The aerodynamic context adjustment corresponds with a product of a so-called Kalman gain matrix and the set of comparison
20 vectors that express the comparison result 416. The aerodynamic context adjustment is thus also in the form of a set of vectors, namely aerodynamic context adjustment vectors.

The Kalman gain matrix may be determined on the basis of the degree of uncertainty about the new estimated aerodynamic context 413, which is expressed by the model-based new set of state vectors. The Kalman gain matrix may further be determined
25 on the basis of information on precision of the actual measurements 415, and an approximated relationship between state variables and measurements, which may be expressed as covariances. The Kalman gain matrix determines the degree of adjustment mentioned hereinbefore in the present embodiment, which is based on an ensemble Kalman filter architecture.

30 The analyzer 404 may subtract the aerodynamic context adjustment from the new estimated aerodynamic context 413, which is model-based. Accordingly, the analyzer 404 provides an adjusted new estimated aerodynamic context 417 in which the actual measurements 415 carried out by the follower aircraft 102 are accounted for. The adjusted new estimated aerodynamic context 417 is also in the form of a set of state vectors,

The covariance inflator 405 enhances differences between state vectors in the adjusted new estimated aerodynamic context 417. This covariance inflation prevents a situation where the Kalman gain matrix is populated with relatively small values making that the degree of adjustment is insignificant. In such a situation, the actual measurements
5 415 would not be accounted for, or at least not sufficiently be accounted for, which is generally not desired. The covariance inflator 405 may add a random vector to a state vector in the set concerned, whereby the random vector may have a Gaussian distribution and zero mean value. The covariance inflator 405 may further enhance a difference between the state vector and the mean state vector 418 of the set according to a technique
10 that is referred to as relaxation to prior spread.

The covariance inflator 405 provides a final new set of state vectors, which expresses the estimated aerodynamic context 406 that will serve as a basis for a new iteration.. The new iteration will start with the aircraft state propagator 401 generating a model-based new set of state vectors as described hereinbefore.

15

NOTES

The embodiments described hereinbefore with reference to the drawings are presented by way of illustration. The invention may be implemented in numerous different ways. In order to illustrate this, some alternatives are briefly indicated.

20

The invention may be applied in numerous types of products or methods related to wake sensing. In the embodiments presented hereinbefore, a wake sensing method has been described that is based on an ensemble Kalman filter architecture. In other embodiments, wake sensing in accordance with the invention may be based on another architecture, such as, for example, an unscented Kalman Filter, a particle filter, or a
25 neural network. In principle, any architecture capable of taking into account a relatively strong non-linear dynamic behavior may be suitable.

There are numerous different ways of modeling a wake for the purpose of wake sensing in accordance with the invention. In the presented embodiments, a wake model is used based on two rotating vortex tubes. In other embodiments, a wake model
30 may comprise a single rotating vortex tube, or another aerodynamic entity, or set of aerodynamic entities, that may sufficiently accurately represent aircraft wake.

In general, there are numerous different ways of implementing the invention, whereby different implementations may have different topologies. In any given topology, a single entity may carry out several functions, or several entities may jointly

carry out a single function. In this respect, the drawings are very diagrammatic. For example, the wake sensing as well as flight control in accordance with the invention may at least partially be carried out by various computing resources in a distributed manner, which is generally referred to as “cloud computing”. Furthermore, there are numerous functions
5 that may be implemented by means of hardware or software, or a combination of both. A description of a software-based implementation does not exclude a hardware-based implementation, and vice versa. Hybrid implementations, which comprise one or more dedicated circuits as well as one or more suitably programmed processors, are also possible. For example, various functions described hereinbefore with reference to the
10 figures may be implemented by means of one or more dedicated circuits, whereby a particular circuit topology defines a particular function.

There are numerous ways of storing and distributing a set of instructions, that is, software, which allows wake sensing as well as flight control in accordance with the invention. For example, software may be stored in a suitable device readable medium,
15 such as, for example, a memory circuit, a magnetic disk, or an optical disk. A device readable medium in which software is stored may be supplied as an individual product or together with another product, which may execute the software. Such a medium may also be part of a product that enables software to be executed. Software may also be distributed via communication networks, which may be wired, wireless, or hybrid. For example,
20 software may be distributed via the Internet. Software may be made available for download by means of a server. Downloading may be subject to a payment.

The remarks made hereinbefore demonstrate that the embodiments described with reference to the drawings illustrate the invention, rather than limit the invention. The invention can be implemented in numerous alternative ways that are within
25 the scope of the appended claims. All changes that come within the meaning and range of equivalency of the claims are to be embraced within their scope. Any reference sign in a claim should not be construed as limiting the claim. The verb “comprise” in a claim does not exclude the presence of other elements or other steps than those listed in the claim. The same applies to similar verbs such as “include” and “contain”. The mention of an element
30 in singular in a claim pertaining to a product, does not exclude that the product may comprise a plurality of such elements. Likewise, the mention of a step in singular in a claim pertaining to a method does not exclude that the method may comprise a plurality of such steps. The mere fact that respective dependent claims define respective additional

features, does not exclude combinations of additional features other than those reflected in the claims.

CLAIMS:

1. A method of sensing a wake (109) produced by a leader aircraft (101) and experienced by a follower aircraft (102), the method comprising repetitively carrying out the following two operations in an iterative manner:
 - estimating measurements (311) carried out by the follower aircraft based on
5 a simulated response of the follower aircraft to an estimated aerodynamic context (309) that includes, on the one hand, a model (204) of the wake and an estimated position (207) of the follower aircraft with respect to the model of the wake and, on the other hand, data indicating aerodynamic effects experienced by the follower aircraft due to its own motion; and
 - 10 - adjusting the estimated aerodynamic context based on a comparison between the measurements that have been estimated and actual measurements (312) carried out by the follower aircraft, aiming to reduce a deviation between the measurements that have been estimated and the actual measurements;
the method further comprising:
 - 15 - extracting information (313) on the wake from the estimated aerodynamic context.
2. A method of sensing a wake according to claim 1, wherein the model (204) of the wake comprises at least one vortex tube (202, 203) positioned with respect to a
20 reference axis (206), the estimated position (207) of the follower aircraft (102) being relative to the reference axis.
3. A method of sensing a wake according to any of claims 1 and 2, wherein the simulated response of the follower aircraft (102) is based on an aerodynamic model of the
25 follower aircraft and a control behavior implemented by a flight control module in the follower aircraft.
4. A method of sensing a wake according to claim 3, wherein the aerodynamic model of the follower aircraft (102) is based on at least one of the following aerodynamic

modelling techniques: Prandtl's lifting line, doublet lattice method, and vortex lattice method, an empirical model based on calibrated coefficients.

5. A method of sensing a wake according to any of claims 1 to 4, wherein the
5 measurements that are estimated (311) and actually carried out (312) comprise measurements typically carried out by commercial aircraft including at least one of the following measurements: angle of incidence, angle of slip, inertial position, velocity, attitude, angular velocity, translational acceleration, and angular acceleration.
- 10 6. A method of sensing a wake according to any of claims 1 to 6, further comprising:
- obtaining data on the leader aircraft (101); and
- using the data on the leader aircraft in defining the model (204) of the wake.
- 15 7. A method of sensing a wake according to claim 7, wherein the data on the leader aircraft (101) indicates a mass of the leader aircraft.
8. A method of sensing a wake according to any of claims 1 to 7, wherein the
20 estimating and the adjusting is done by means of a recursive filter (400).
9. A method of sensing a wake according to claim 8, wherein the recursive
filter (400) is one of the following: an ensemble Kalman filter, an unscented Kalman filter, a particle filter, and a neural-network based filter.
- 25 10. A method of sensing a wake according to any of claims 8 and 9, wherein the recursive filter (400) operates on a state vector (407-411) that comprises at least one variable of the model (204) of the wake, at least one variable expressing the position of the follower aircraft with respect to the model of the wake, and a set of variables of a model of the follower aircraft as a dynamic system.
- 30 11.. A method of sensing a wake according to any of claims 1 to 10, wherein the method is carried out by a flight computer (300) in the follower aircraft (102).

12. A method of controlling a flight of a follower aircraft that flies behind a leader aircraft, the method comprising:

- carrying out a method of any of claims 1 to 11 to obtain information on a wake (109) produced by the leader aircraft (101) and experienced by the follower aircraft (102); and

- using the information (313) on the wake obtained to define a target (305) for a flight controller (301) in the follower aircraft (102).

13. A method of controlling a flight according to claim 12, wherein using the information (313) on the wake comprises:

- filtering the information on the wake that is extracted from the estimated aerodynamic context (309); and

at least one of the following operations based on information on the wake that has been filtered:

- detecting generic patterns of the wake; and

- detecting at least a turbulence characteristic in the wake.

14. A computer program enabling a processor to carry out at least one of the following methods: a method of sensing a wake according to any of claims 1 to 11 and a method of controlling a flight according to any of claims 12 and 13.

15. A flight computer (300) adapted to carry out at least one of the following methods: a method of sensing a wake according to any of claims 1 to 11 and a method of controlling a flight according to any of claims 12 and 13.

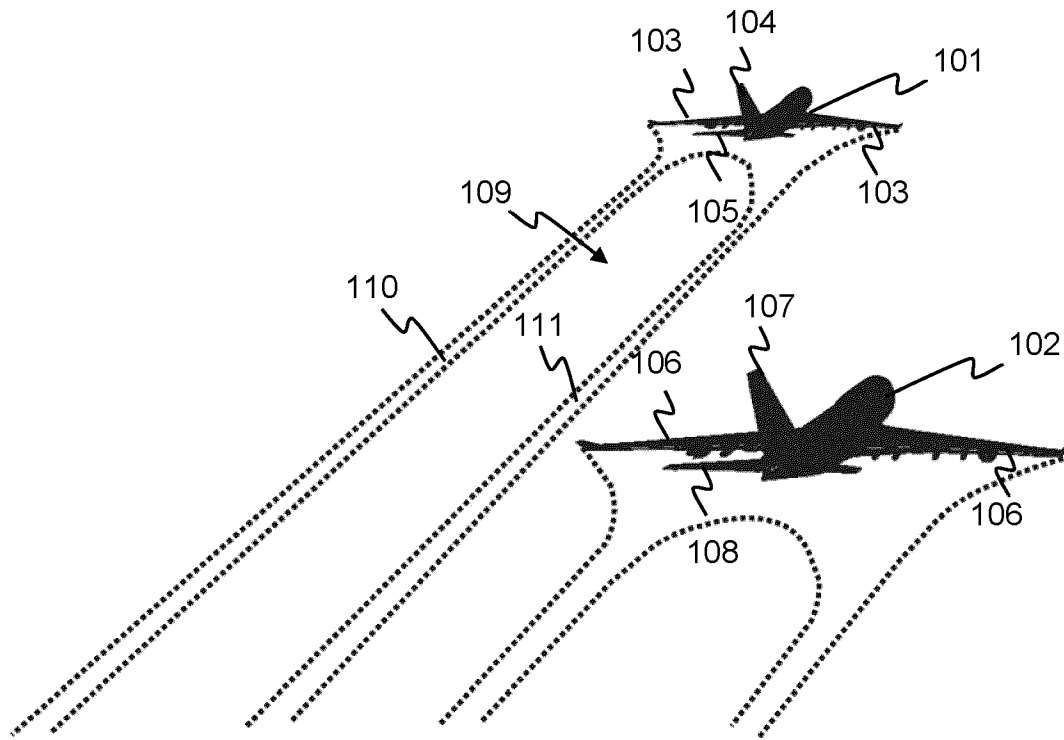


FIG. 1

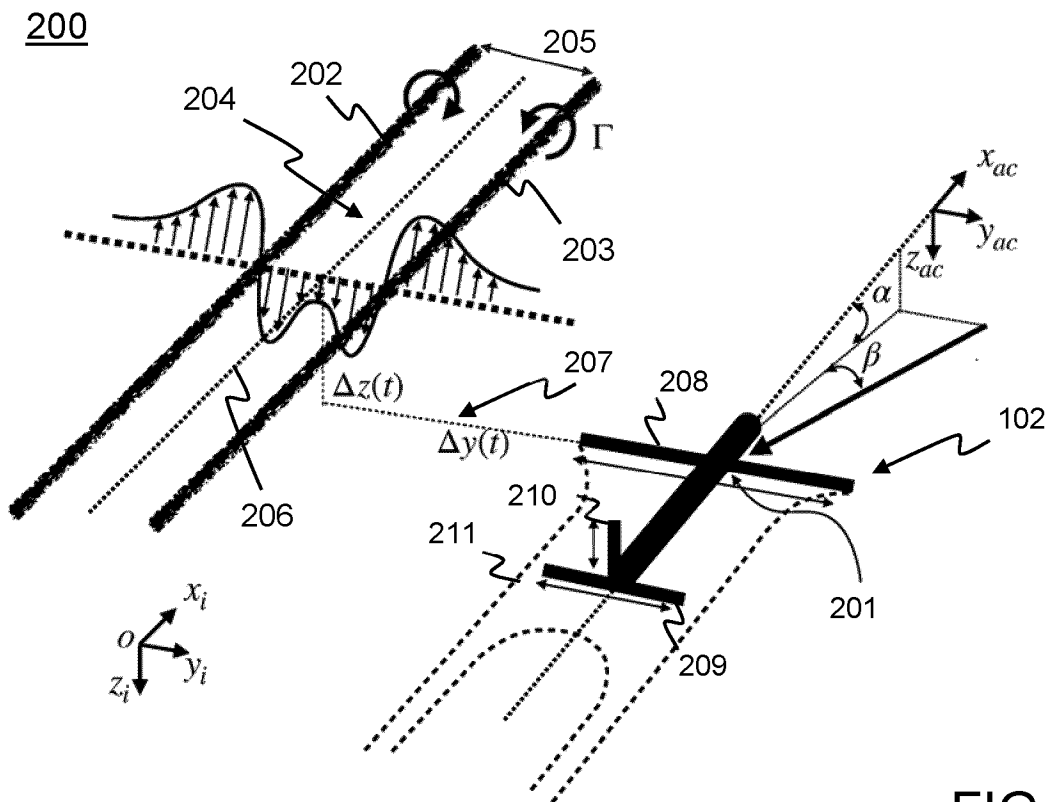


FIG. 2

300

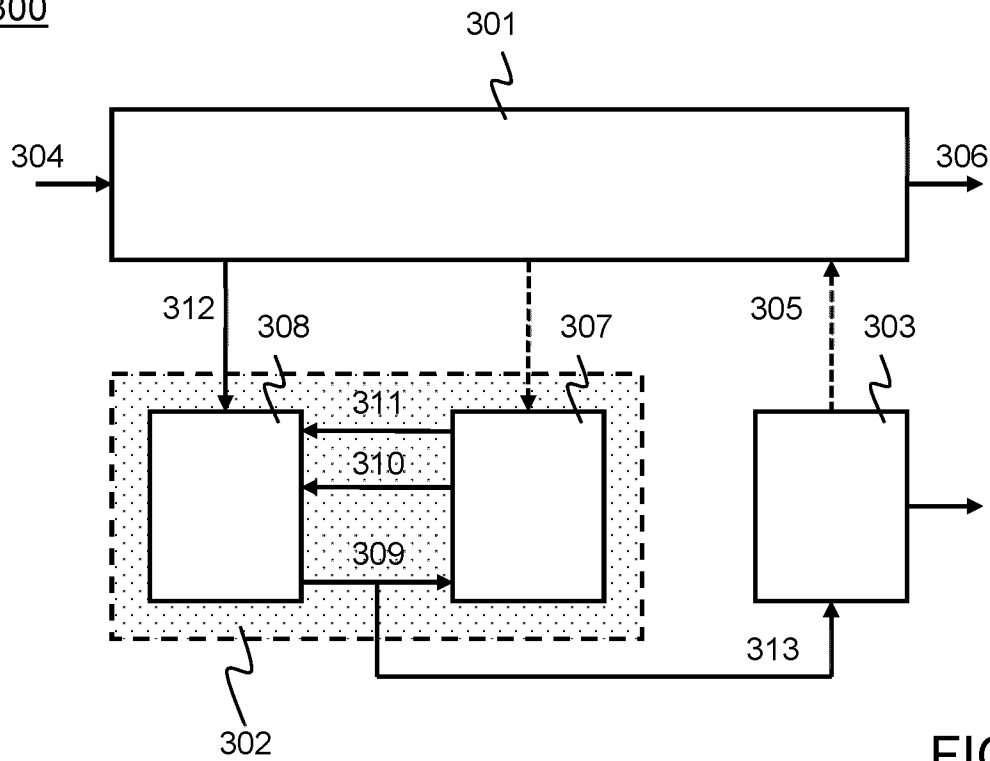
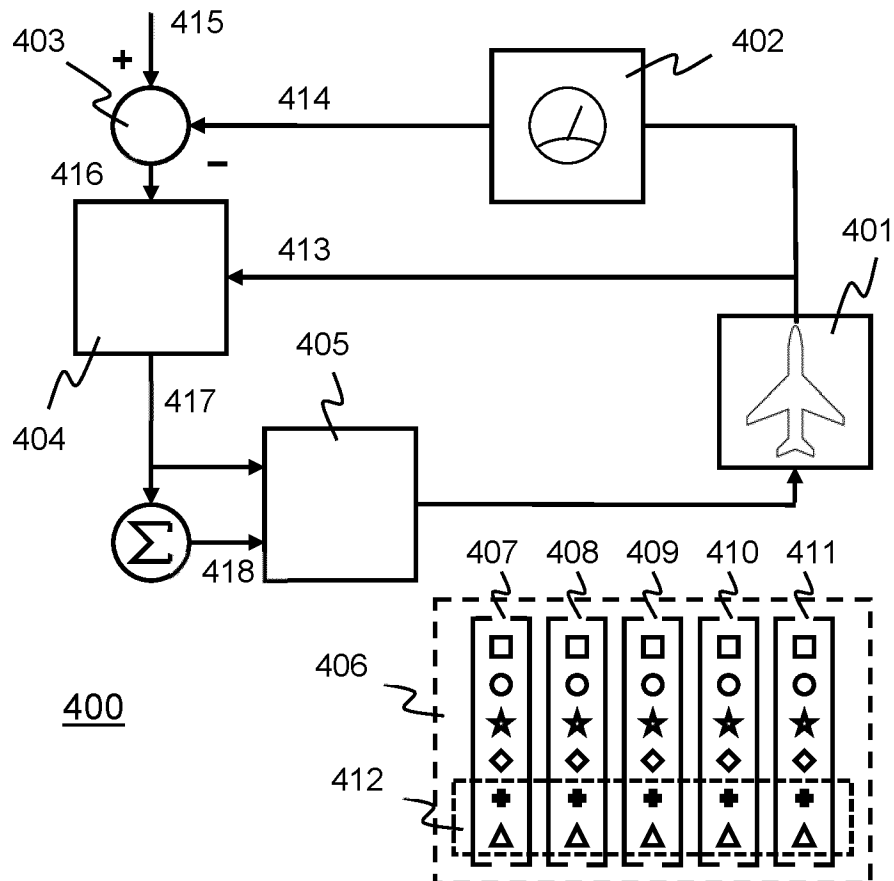


FIG. 3



400

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/071502

A. CLASSIFICATION OF SUBJECT MATTER

INV. G05D1/10 G01C23/00 G08G5/00 B64D45/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G05D G01P B64D G08G G01C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/269612 A1 (FROLOV SERGEY V [US] ET AL) 21 September 2017 (2017-09-21) claims 1-29 figures 1-30	1-15
X	----- US 2014/214243 A1 (WHITEHEAD BRIAN T [US] ET AL) 31 July 2014 (2014-07-31) cited in the application claims 1-35 figures 1,2A,2B,3-8 paragraph [0001] - paragraph [0008] paragraph [0041] - paragraph [0046] paragraph [0055] ----- -/-	1-15



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search

29 October 2021

Date of mailing of the international search report

11/11/2021

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van der Pol, Edwin

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/071502

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
T	RANSQUIN IGNACE ET AL: "Wake Vortex Detection and Tracking for Aircraft Formation Flight", JOURNAL OF GUIDANCE AND CONTROL AND DYNAMICS., [Online] 23 August 2021 (2021-08-23), pages 1-19, XP055856459, US ISSN: 0731-5090, DOI: 10.2514/1.G006028 https://arc.aiaa.org/doi/full/10.2514/1.G006028 Retrieved from the Internet: URL:http://dx.doi.org/10.2514/1.G006028> [retrieved on 2021-10-29] the whole document -----	1
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2021/071502

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			EP 2772817 A2 03-09-2014
			ES 2649474 T3 12-01-2018
			US 2014214243 A1 31-07-2014
